APPENDIX 2 [1]

Beam Line Bremsstrahlung Shielding at the NSLS

[1] This document is the basis for the bremsstrahlung shielding requirements established for all beam lines with line of sight visibility into the ring vacuum pipe. It was initially included in the original NSLS SAD.

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MEMORANDUM

DATE: April 9, 1982

TO: K. Batchelor, Chairman, NSLS Safety Committee

FROM : W. Thomlinson, R. Watson, L. Blumberg

SUBJECT: Beam Line Bremsstrahlung Shielding at the NSLS

I. INTRODUCTION

The shielding of the NSLS storage rings must be able to deal with maximum credible radiation accidents due to the electron beam being stopped at some spot in a ring and with the maximum credible dosages due to losses during day in, day out operation of the facility. Blumberg and Perlman (BP) considered[1] a maximum credible accident consisting of a short section of the machine vacuum system, in line of sight of a photon port, brought up to atmospheric pressure and interacting with the electron beam to cause bremsstrahlung. Ryder and Holbourn subsequently argued[2] that the radiation hazard from this event was substantially overestimated. We show in this Memo that Blumberg and Perlman's conclusions essentially survive critical reinspection.

Day in, day out losses are important because a ring will be loaded two or three times-during a working day with a large part, if not all, of the electrons lost with each loading. This occurs for 250 working days a year for a typical person on the experimental floor. We will consider the radiation due to the interaction of the electron's beam with the residual gas in the machine vacuum of 10^{-9} -10^{-10} torr. This is of concern since some of this is in direct view of a photon line. It will be found to be unimportant. Consideration of this is followed by a review of where electron losses are expected to occur during normal operation of the ring and this will suggest a maximum credible level of radiation which must be shielded against for such operations. As was the case with the concrete shielding,[3] it is the normal operating losses over a working year rather than an accidental dump which makes the most severe demands on shielding.

II. Sudden Loss Due to Bringing a Segment of a Ring Up to Air

Consider that a short segment of the machine vacuum, of 15-20 cm length, is suddenly brought up to atmospheric pressure. As the electron bunches traverse this region, some of the electrons will interact with the gas and emit bremsstrahlung. The target is thin, of the order of 5 x 10^{-4} radiation lengths, but is traversed many times by any given electron bunch. The frequency of traversal is simply the speed of the electrons divided by the circumference of the ring in question or ~2 x 10^{6}/sec for the X-ray ring and roughly three times this for the UV ring. Given the thickness of the segment, about a millisecond is the time necessary to absorb the electron beam and as this is of the order of the time for valves to close and the ring to turn off, it is very conservative to assume that all the electrons in the ring are involved in bremsstrahlung production. Then the total energy in the bremsstrahlung beam is:

$$E_\gamma = f_{tot} <k> N_e \qquad (1)$$

This is BP's Eq (9) where N_e is the number of electrons stored in the ring (1.06 x 10^{12} for tne VUV and 3.9 x 10^{12} for the X-ray at 2 GeV and 0.5 amp), $<k>$ is the average bremsstrahlung energy (45 MeV in the VUV and 180 MeV in the X-ray), and f_{tot} is the number of bremsstrahlung associated with any given electron. BP estimated f_{tot} by asking the probability of any given electron surviving in orbit after one collision in order to be involved in another. From this they obtained:

$$f_{tot}\,(\mathrm{VUV}) = 2.94 \text{ and } f_{tot\,(\mathrm{X\text{-}ray})} - 2.42$$

and then:

$$E_\gamma\,(\mathrm{VUV}) = 22.4\ \mathrm{J} \qquad (2a)$$

and:

$$E_\gamma\,(\mathrm{X\text{-}ray}) = 272\ \mathrm{J} \qquad (2b)$$

Somewhat larger values are obtained if it is assumed that the entire energy of the stored el is converted into bremsstrahlung, i.e.;

$$E_\gamma = E(\mathrm{electrons})\, N_e$$

or:

$$E_\gamma\,(\mathrm{VUV}) = 119\ \mathrm{J} \qquad (3a)$$

and:

$$E_\gamma\,(\mathrm{X\text{-}ray}) = 1248\ \mathrm{J} \qquad (3b)$$

which are the maximum energies possible.

Following BP's method of converting these energies to unshielded absorbed doses one obtains from Eqs. 3).

$$D(\mathrm{VUV}) = 20{,}000 \text{ Rads at 5 m}$$

and:

$$D(\mathrm{X\text{-}ray}) = 170{,}000 \text{ Rads at 10 m} \qquad (4b)$$

where 5 and 10 m are typical viewing distances along photon beam pipes on the two rings. . use a more conventional technique for converting to dosage which involves dividing the E_γ by the electron energies to define equivalent quanta and employing a conversion due to Tesch[4] to obtain Rads. This scheme yields values for the doses D which are roughly an order of magnitude smaller than Eqs (4).

III. Bremsstrahlung Due to the Residual Gas in Normal Operation

The same 15-20 cm of the vacuum chamber considered above can be seen along a photon beam line during normal storage ring operation. The storage ring will operate at a pressure of 10^{-9}-10^{-10} torr, which is 1.3 x (10^{-12}-10^{-13}) of the atmospheric pressure (760 torr) considered for the sudden failure. Knowing this, it is easy to scale the results of the preceding section. If it takes

100 μsec for the majority of electrons in orbit to be lost due to bremsstrahlung production at 1 atmosphere in the 15-20 cm path, then the time necessary for the equivalent loss at normal machine vacuum is:

$$\tau = \frac{100 \times 10^{6}}{1.3x\left(10^{-12} - 10^{-13}\right)} \sim 10^{8} \text{ to } 10^{9} \sec \tag{5}$$

A normal work year of 50 forty hour weeks is 7 x 10^6 sec which is one to two orders of magnitude smaller than τ implying that the integrated radiation dose seen along a photon beam line over a year is one to two orders of magnitude smaller than the sudden accidental event. Photon beam ports viewing straight sections housing wigglers or undulators will typically see an order of magnitude greater length of machine vacuum and hence will receive a dose which is of the order of, or an order of magnitude smaller than, the accidental dump case.

The rate of loss of electrons due to residual gas bremsstrahlung production can he calculated by noting that for a high energy electron the energy loss in passing through material is

$$dE = -E_o \frac{ds}{\chi} = \frac{-E_o v \ dt}{\chi}$$

where χ is the radiation length of the material. At a pressure of 10^{-9} torr the radiation length for 60% H_2, 40% CO is ~4 x 10^{14}m. Thus, for a 4 hour fill time the mean energy lost by an electron is

$$\frac{\Delta E}{E_o} = \frac{c \ \Delta t}{\chi} = \frac{3 \times 10^{8} m/\sec 4/3 \times 10^{4} \sec}{4 \times 10^{14m}} = 1\%$$

Thus, ~1% of the beam energy at 10^{-9} torr will go into bremsstrahlung. This energy will be distributed around the rings in the same manner as is the residual gas.

The fraction of electrons lost due to gas bremsstrahlung interactions can also be estimated by scaling the estimates made earlier. First, τ must be reduced by the ratio of the ring circumference to the 20 cm path length since electron losses occur uniformly around the ring. The result is the time required to lose the full beam in the full ring. The fraction lost during a single 4 hour fill is then found to be of the order of 4.8%.

IV. Location of Electron Losses During Normal Operations

Neglecting injection and the effects of inserting devices which act as scrapers, the normal processes by which electrons will be lost involve electron-electron, bunch-bunch, and to a lesser extent, electron-residual gas scattering which leave electrons in orbits and at energies outside the phase space region in which they can be maintained in energy by the RF system (see, for example, Krinsky, et al[6]). Whether initially at too high or too low an energy to be in the RF bucket, the electron will lose energy and spiral inwards in orbit until it collides with the inner vacuum chamber wall. For a vacuum chamber of uniform cross-section, this will most probably occur where the dispersion function, η, is a maximum. This quantity relates the horizontal error in orbit positions, Δx, to the error in electron momentum, Δp, namely:

$$\Delta x = \frac{\eta \Delta p}{p} \tag{6}$$

(see Eq. 73 in ref. 6 and the associated discussion). This is plotted for the NSLS X-ray ring in Fig. 1 and similar behavior occurs in the VUV ring. The electron optics of the NSLS rings were designed so that η is zero in the long straight sections, housing wigglers and undulators, is near zero in the bending magnets and peaks in the middle of the short straight sections between pairs of bending magnets. The initial collision of an electron with the vacuum chamber is expected to occur on the inside wall of these short straight sections with a 95% probability. Therefore, there must be a concentration of shielding lead alongside and downstream of these short straights.

It is seen from Fig. 1 that the maximum η for the X-ray ring is 1.4m (1.5m for the VUV). Since the distance between the center of the vacuum chamber and inner wall is 0.04m, the momentum deviations at which electrons hit the wall is $\frac{\Delta p}{p} = \frac{0.04}{1.4}$ or roughly 3%. Now, it was noted in Section III that roughly five percent of the electrons will be lost due to residual gas bremsstrahlung production during a four-hour shift. The typical energy or momentum loss in such an event (see Section III) is 6% in the VUV and 9% in the X-ray ring. These electrons can be expected to hit the vacuum wall in or just upstream of the first short straight section encountered after the event. This has two implications: first, electrons will not survive to be involved in a second event of this nature and hence the estimates of Sections II and III are over estimates, and second, if the electrons make it to the next short straight, they are expected to hit the wall when $0.04/\eta$ equals 0.06 in the VUV and 0.09 in the X-ray rings, i.e., when η equals a half and one-third its maximum values, respectively. This implies that, while most electrons are lost by gradual processes and first hit the wall at the center of the short straights where η is a maximum, some one-percent of the electrons will tend to hit the wall upstream of the center. The above observations do not apply to electrons involved in substantial bremsstrahlung energy losses in regions where η is large. The distribution of where these electrons will hit the wall is, as of this writing, unknown. Orbit calculations are being done to help answer the question. This discussion implies that shielding must be considered along the short straight sections and extending back into the dipole magnet.

V. <u>The Maximum Credible Steady State Dosage</u>

Granted that there are eight short straight sections in the X-ray ring (and four in the VUV), a maximum credible estimate of the dosage occurring and hence the shielding needed along a photon beam line can be made by assuming that one-eighth (one-fourth) of the electrons are stopped in one short straight section, that their energy is converted to bremsstrahlung, and that this impinges on a single photon port. If no bremsstrahlung attenuation is credited to the aluminium, steel and lead along the straight section and, if all the electrons in a loading are lost, then from Eqs. 4 we have unshielded dosages of:

$$\mathrm{D(VUV)} = \frac{20{,}000}{4} = 5{,}000 \text{ Rads/Load at 5m} \tag{7a}$$

and:

$$\mathrm{D(X-Ray)} = \frac{170{,}000}{8} = 20{,}000 \text{ Rads/Load at 10m} \tag{7b}$$

for one cycle of machine operation. The numbers are an order of magnitude less if one prefers the equivalent quantum method of estimating dosage.

It is expected that an electron beam will have a half life of ~4 hours. After four hours the beam will be dumped and a new beam injected, though it may prove possible to replenish the electrons in the existing beam without dumping it. In any case, it appears reasonable to assume two complete loadings per working day. Granted 250 working days a year, the allowable dosage per loading must be 1/500 of the allowable annual dosage. Let us take this to mean that Eqs (7) must be reduced by shielding to less than 1 mRad/Load (i.e., 0.5 rad/year for the maximum allowable radiation level), a factor of 5 x 10^{-8} for the X-ray ring and 2 x 10^{-7} for the UV ring. The necessary lead shielding can be estimated in three ways:

1) Dinter and Tesch[5] report a measured effective linear absorption coefficient of 0.47cm^{-1} for bremsstrahlung in lead. This implies that ~14" of lead is needed on the X-ray ring along the direction of the beam, and 13" for the UV ring.
2) One can take the estimate of attenuation following Rossi[8] which accounts for the electromagnetic cascade. This is summarized in Fig. 2 for a 2.5 GeV electron beam. One obtains a required thickness of lead of 55 radiation lengths or about 12" for the X-ray ring.
   Dinter and Tesch made measurements[5] of the dose and shielding parameters of electron bremsstrahlung radiation produced by a high energy electron beam impinging on iron targets of varying thickness. The bremsstrahlung production is concentrated in the forward direction in a cone whose opening angle is a fraction of a milliradian and, unfortunately, the smallest angle of observation was necessarily much larger than this. Their measured dosages are thus much smaller than the numbers above. Dinter and Tesch's results do suggest that radiation generated at right angles to the forward direction is only four or five orders down in magnitude. This is still too large to be ignored in shielding considerations.
   The results of Monte Carlo calculations (Fig. 6 and 7 of Ref. 5), indicate that the bremsstrahlung produced at angles of 30° and 90° is 2 or more orders of magnitude lower in energy than in the forward direction. The energies are also below the energy necessary for resonant neutron production. Referring to their Figure 5, it is clear that the concrete shielding provided by the X-ray tunnel should provide adequate shielding.
3) The most straightforward estimates for the lead shielding along a beam line are probably those obtained using the data of Ref. 9, G. Bathow, et al, for the isodoses in lead for both longitudinal and radial directions. These estimates are not greatly different than those above, and will be used to make recommendations for beam line lead bremsstrahlung shielding. However, these estimates have calculated doses at the edge of a shield. We will choose to assume that a worker's annual occupancy of the experimental floor is approximated by
   standing ~l.5m from a shield during 500 fills of the ring. In actuality, there will be many shields, the dose from each one will be smaller than this. Efforts will be made to keep the shielding as close to the ring as possible.

We would like to make the dose less than 0.5 rad/yr.at a distance of 1.5 meters from the lead shielding. The effective source of radiation will be a volume in the lead with a typical dimension on the order of 15cm diameter. The R^{-2} factor will then be 2.5 x 10^{-3}. Thus, the yearly dose at the surface of the lead can be D=200 rad/yr.

Assume 1/8 of the electrons in the VUV ring and 1/16 of the electrons in the X-ray ring lose their energy down a beam line each fill. For 500 fills/year that means a beam line will see N electrons where N = 500 x 1/8 x N_e for the UV and N = 500 x 1/16 x N_e for the X-ray ring. N_e is 1.06 x 10^{12} for the VUV and 3.9 x 10^{12} for the X-ray ring. Thus, for the UV ring, N = 6.63 x 10^{13} e/yr and for the X-ray ring N=1.22 x 10^{14} e/yr.

The proper isodose curve on Fig. 3 is then found by:

$$\text{ISODOSE} = \text{D/N}\ \frac{\text{rad}}{\text{e}}$$

The values of the depth intercept in units of the radiation length X_o and the maximum value of width in units of the Moliére length X_m then define the length of the lead and the thickness required in all directions normal to the beam, respectively.

<u>X-Ray</u>:
- ISODOSE = 1.6×10^{-12} rad/e
- Length $= 34X_o {}^{=} 19.8\text{cm} = 7.8''$
- Thickness $= 4.1X_m {}^{=} 5.3\text{cm} = 2.1''$

<u>VUV</u>:
- ISODOSE = 3×10^{-12}
- Length $= 31X_o {}^{=} 18.0\text{cm} = 7.1''$
- Thickness $= 3.4X_m = 4.4\text{cm} = 1.7''$

In order to determine the placement of lead shielding along a beam line to obtain line-of-sight shielding, the proper aperture for the bremsstrahlung radiation is the lead collimation. The collimation is provided by the tail-pieces, the ring belt and the lead to the inside of the ring. Since the electrons strike the inner wall, the lead on the inside of the ring prevents line of sight to the inside walls of the straight sections. The effective source for the bremsstrahlung is not a simple point source at the nominal tangent to the beam. In the shielding considerations, the source must be taken as a rectangle at the tangent with a vertical extent ± 10mm from the median plane, extending horizontally 30mm towards the outside of the orbit and 100mm towards the inside of the orbit. All lines of sight through the lead collimators back to this extended source must be blocked by the above mandatory lead shield thicknesses.

Any place along a beam line where the direct bremsstrahlung radiation is outside the beam pipe will be an exclusion area for personnel.

VI. <u>Neutron Shielding</u>

When the lead stops the high energy radiation some conversion of personnel photon dose to neutron dose occurs ($\sim 10^{-4}$). The concrete walls around the X-ray ring, and those along the VUV ring will suffice to attenuate the neutrons from the internal shielding. However, the actual bremsstrahlung dose to any particular lead shield, and thus the subsequent conversion to neutrons, is so uncertain that we feel it is unnecessary to initially install neutron shielding around each beam line shield. Once operation begins, neutron dose levels must be monitored, and neutron shielding installed wherever necessary. Thicknesses of neutron shielding tend to be large so the most effective reduction of neutron dose may come from making apertures in the lead shields smaller, thus moving the source away from the experimenters. Ideally, the lead shielding would be inside the concrete shield wall.

VII. <u>Conclusions</u>:

The calculations and recommendations presented in this Memo have been based on extreme worst case assumptions for the normal beam losses. No attempt has been made to estimate an occupancy factor for any individual. We feel that the radiation levels have, therefore, probably been overestimated by two or three orders of magnitude.

Based on the calculations in this Memo, the following conclusions are then reached:

1. The residual gas bremsstrahlung dose for one year of operation is expected to be roughly equivalent to a single sudden event for straight sections, and less on a bending magnet port which does not see a straight.

2. The maximum credible steady state dosage due to electrons hitting the inner wall of short straight sections is higher than the extreme gas bremsstrahlung accident.

3. The recommended minimum dimensions of lead which must be used to provide line-of-sight beam line bremsstrahlung shielding are tabulated below:

Parallel to Beam		Normal to Beam
X-Ray	8"	2"
VUV	7"	1.7"

4. The beam line shielding installed must be monitored and radiation levels measured during operation. The position and thickness of the shielding must then be adjusted to satisfy the allowed dose conditions.

5. The need for neutron shielding around the lead bremsstrahlung shields will be evaluated as necessary when operations begin.

REFERENCES

1) L. Blumberg and M. L. Perlman "Maximum Credible Radiation Accident" NSLS Memo, May 15, 1980.

2) R. Ryder and H. P. Holbourn, "Addendum to HP81/139, Daresbury, November, 1981.

3) National Synchrotron Light Source Design Handbook, Sect. 29.

4) K. Tesch, Nubleonik, 8 264 (1966).

5) H. Dinter and K. Tesch, Nuc. Inst. and Meth., 143, 349 (1977).

6) S. Krinsky, M. L. Perlman and R. E. Watson, "Characteristics of Synchrotron Radiation and Its Sources," to be published in a handbook by North-Holland.

7) National Synchrotron Light Source Design Handbook, Sect. 3.2.

8) Rossi, High Energy Particles, p. 251 (1961).

9) G. Bathow, E. Freytag, K. Tesch, R. Kajikawa, and M. Köbberling, Second International Conference on Accelerator Dosimetry and Experience, U.S. Atomic Energy Commission, CONF-691101, p. 222 (1969).

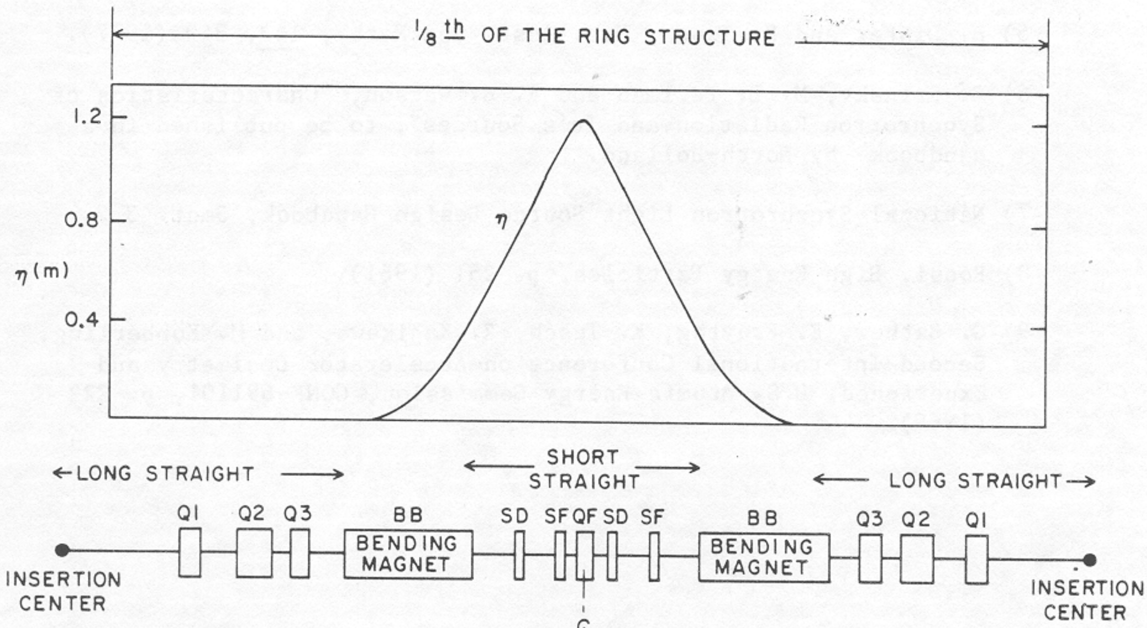
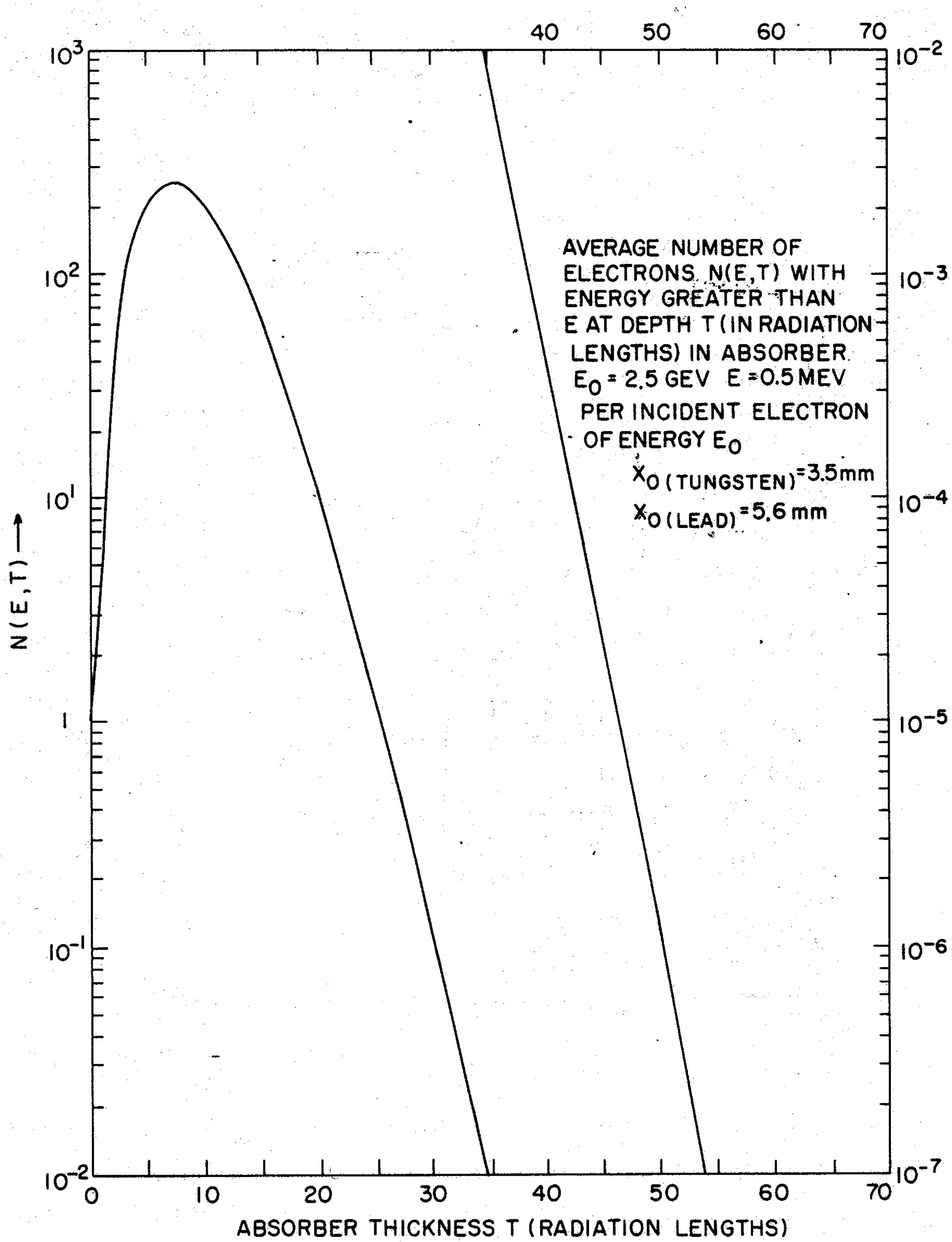


Figure D-1. The momentum dispersion function for the NSLS x-ray ring.



AVERAGE NUMBER OF
ELECTRONS N(E,T) WITH
ENERGY GREATER THAN
E AT DEPTH T (IN RADIATION
LENGTHS) IN ABSORBER
E0 = 2.5 GEV E = 0.5 MEV
PER INCIDENT ELECTRON
OF ENERGY E0
X0 (TUNGSTEN) = 3.5 mm
X0 (LEAD) = 5.6 mm
N(E,T)
ABSORBER THICKNESS T (RADIATION LENGTHS)
0
10
20
30
40
50
60
70
10^3
10^2
10^1
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7

Figure D-2.

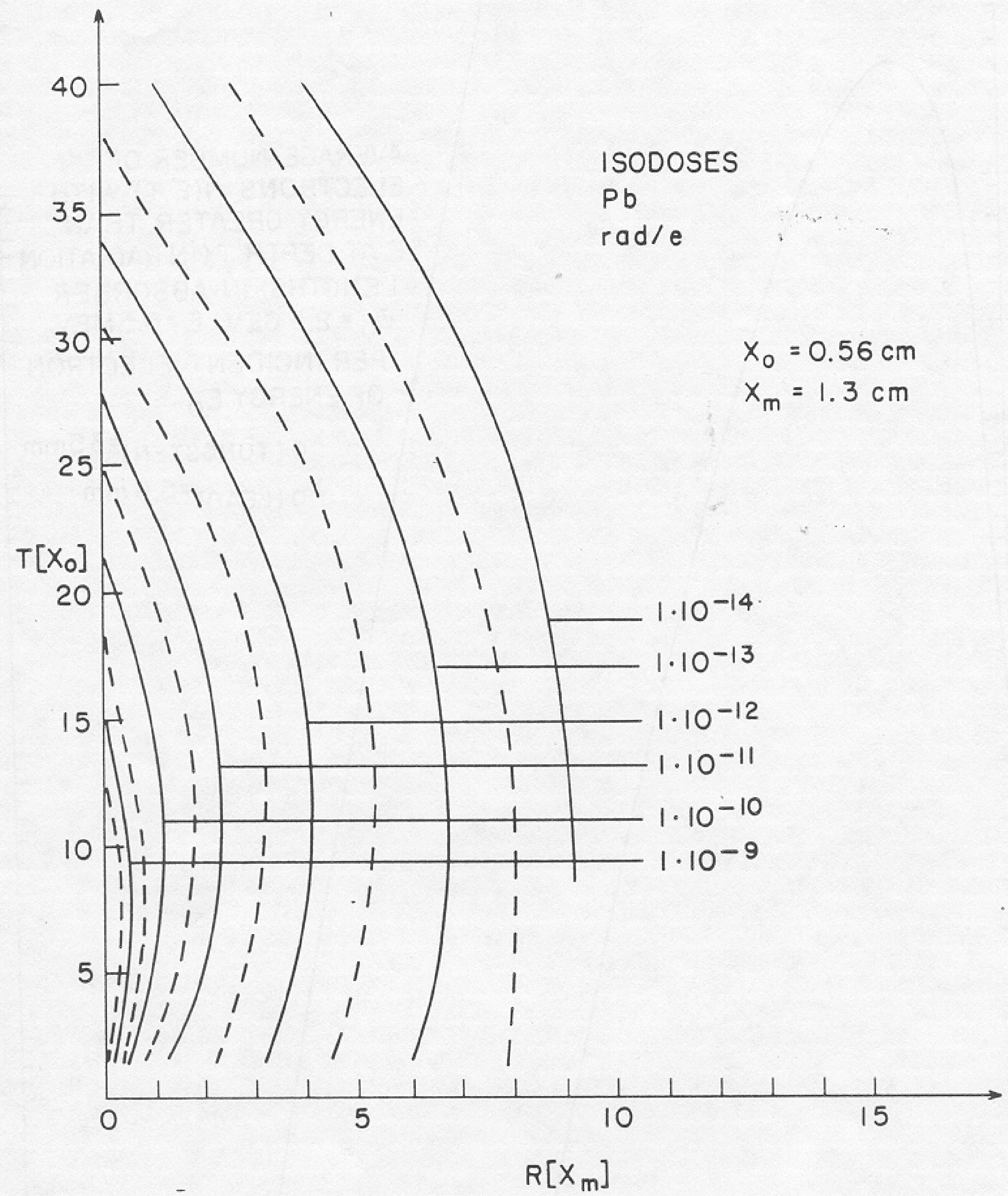


Figure D-3. Isodoses for lead.